THE ANALYSIS OF SPECTRA OF NOVAE TAKEN NEAR MAXIMUM

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ABSTRACT

We have recently begun a project to analyze ultraviolet spectra of novae obtained at or near maximum optical light. These spectra are characterized by a relatively cool continuum with superimposed permitted emission lines from ions such as Fe II, Mg II, and Si II. In contrast, the spectra obtained late in the outburst show only emission lines from highly ionized species and in many cases these are forbidden lines. These ultraviolet data will be used in combination with recent calculations of spherical, expanding, stellar atmospheres for novae to determine elemental abundances by spectral line synthesis. This method is extremely sensitive to the abundances and completely independent of the nebular analyses usually used to obtain novae abundances.

1. Introduction

The initial eruption of a nova is very rapid, with the major part of the rise to visual maximum taking place in a day or less. During the rising branch of the light curve, the nova basically consists of an optically thick, uniformly expanding shell. As the expansion is very rapid and the luminosity fairly constant, the effective temperature smoothly declines and reaches a minimum of 4000K-7000K at visual maximum (e.g., Gallagher and Ney 1976; Gallagher and Starrfield 1978). At this time the material, which is mostly hydrogen (except in some very unusual novae), begins to recor.bine and the pseudo-photosphere begins to move inward in mass. In fact, as has been emphasized by Gallagher and Starrfield (1978), the optical maximum is purely an opacity effect caused by the large decrease in opacity when hydrogen recombines.

It is only during this time that pure absorption line or P-Cygni profiles are seen and are accessible to analysis (Williams et al. 1981; Starrfield 1987). In fast, optically luminous, novae the primary shell will become optically thin in a few days; thereafter, the optical spectral region is dominated by bremsstrahlung and hydrogen bound-free emission (Gallagher and Ney 1976; Ennis et al. 1977; Martin 1987). However, because the ultraviolet opacity is higher, the ultraviolet region of the spectrum remains optically thick for a much longer period and the continuum can be present for days to weeks. The cause of the enhanced ultraviolet opacity is the presence of thousands of lines from the astrophysically abundant elements such as iron and magnesium and other elements with similar atomic structure. In other astrophysical environments this is called the "iron forest".

In a slow (low optical luminosity) nova, such as Nova Vul 1984 #2, continuous mass loss, via a radiation pressure driven wind, maintains a low temperature photosphere for several months or years (Geisel et al. 1970; Bath 1978; Ney and Hatfield 1978). Because the radius at which the pseudo-photosphere is formed determines the "effective" temperature of the layers, at luminosities of $10^4 L_\odot$, photospheric radii of 10^{12}cm will produce continuum energy distributions characteristic of F (or later) supergiants. That is exactly what is observed for novae.

Ultraviolet data have now been obtained for more than a dozen novae with the IUE satellite. The data obtained late in the outburst have been analyzed and published for many of them (Starrfield and Snijders 1987; Starrfield 1988) while the spectra obtained near maximum optical light have never been analyzed and are seldom shown. Nevertheless, these data are an important source of information about the expanding layers at the beginning of the explosion and now that the techniques have been developed to analyze these data we expect to see this situation change rapidly.

2. Physical Model and Assumptions

In order to proceed with the analysis, some of us have developed a program to calculate model stellar atmospheres (Shaviv, Wehrse, and Wagoner 1984; Spies et al. 1987). These models are calculated with the following assumptions: 1) spherical symmetry (not plane parallel), 2) the density follows a power law with an exponent around 2 or 3 (in contrast to the supernova models that have a density exponent approaching 7 to 10), 3) LTE (including scattering), 4) radiative equilibrium, 5) and the expansion velocity is proportional to the radius. All of the relevant opacity sources are included so that we will be able to calculate the effects of the iron forest (c.f., Baschek and Johansson 1986) and then determine the expansion opacity (Karp et al. 1977).

The original motivation for the development of this code was to analyze the spectra of SN II and to try
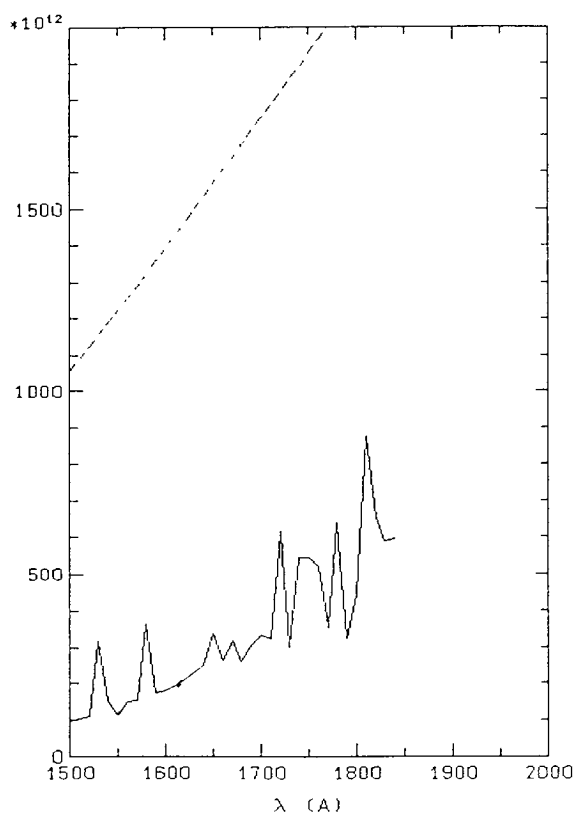
Figure 1. Comparison of a theoretical energy distribution for a line-blanketed, spherical, expanding model atmosphere with the appropriate black-body energy distribution. This model had T_e = 10,000K and E(B-V)=0.5. The outer radius was 10^{12}cm and the density exponent was 2.
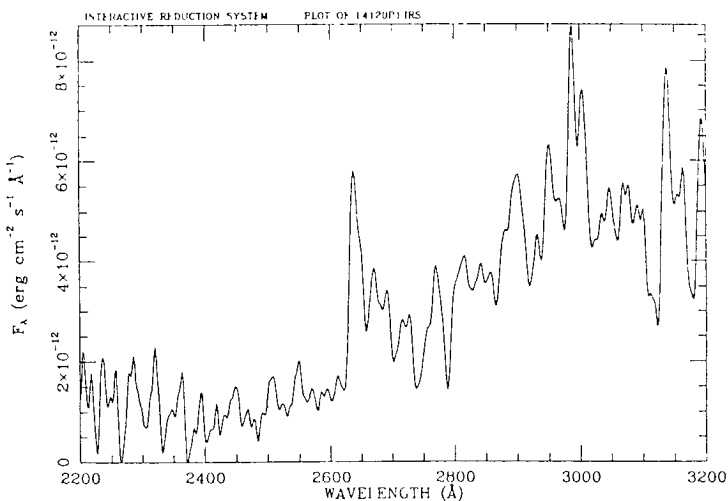

Figure 2b. The LWP image of Nova Vul 1984 #1 taken just after the spectrum shown in Figure 2a. Note that each spectrum is scaled to the strengths of the emission lines in the given spectral region.
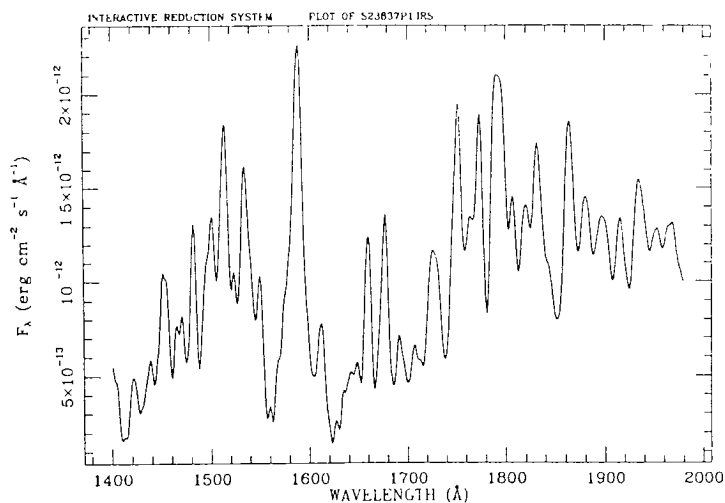

Figure 2a. The SWP image of Nova Vul 1984 #1 taken about 15 days after discovery. This slow nova was still at maximum light. The cool continuum is obvious and this spectrum looks completely unlike spectra obtained later in the outburst. Lyα is present and so strong that the other lines would not have been visible.

and understand the cause of the large ultraviolet opacity in these objects. In fact, it has been shown that the code can be applied to this problem with excellent agreement between theory and observations (Spies et al. 1987).

In Figure 1 we show the results of the initial attempt to calculate a model for a nova atmosphere near maximum. The model atmosphere had a radius of 10^{12}cm, a density law exponent of 2, an effective temperature of 10,000K, E(B-V)=0.5, and included 30,000 lines. The upper line is the equivalent black body curve and shows the large amount of ultraviolet opacity present in this model. It is important to note that even with the large number of blends, there are only a few lines apparent in the spectrum and in order to analyze a nova we will have to do spectral line synthesis.

We are also in the process of developing a method to facilitate our line identifications for novae spectra using a technique similar to that outlined for supernovae spectra by Branch (1987). We use the Saha and Boltzmann equations and the line list of Kurucz and Petrymann (1975) to compute the strongest expected lines in each wavelength interval.

3. IUE Observations of Novae

We have obtained early spectra of numerous nova and in this section we show a few representative LWP and SWP spectra. Figure 2a and 2b shows spectra of Nova Vul 1984 #1 taken on day 245 of 1984 when the nova was at 7.0m; Figure 3a and 3b shows spectra of Nova Vul 1984 #2 taken on day 1 of 1985 when this nova was at 6.3m. Finally, in Figure 4a and 4b we show spectra of Nova And 1986 obtained on day 343 of 1986 when this nova was at 8.8m. This series of spectra emphasize our statements about the structure of the atmosphere at maximum optical light. The cool continuum is obvious and the strongest features are probably caused by Si I and Fe I. Many of the other emission lines are probably blends of lines from elements such as iron, nitrogen, carbon, oxygen, and silicon. Unfortunately, these spectra are too complex for proper line identification and we have also obtained some high dispersion spectra in order to improve our wavelengths [see Sion et al. 1987]. In fact, as can be seen from Figure 1, it is likely that most of the lines that we see are blends.

We also note that there is a general similarity of the early ultraviolet nova spectra with those of SN 1987A obtained on the first day of its outburst. Of course, the lines are much broader in SN1987A and it is much harder to identify the elements leading to the specific blends. In fact, we should not be surprised at the resemblance since, in both cases, we are examining material with a great deal of hydrogen and helium. One motivating factor in this study is to apply the codes designed for studying the supernova to a study of the novae since there is so much more data on novae. In addition, once we have identified the features in the nova spectra, it will then be possible to take the nova spectra, broaden them, use this data to assist in the analysis of the SN spectra, and ultimately determine which elements are contributing to the broad blends in SN 1987A.

4. Summary and Discussion

We have begun an analysis of the early spectra of

novae in an attempt to develope a completely new method (as applied to novae) to determine the elemental abundances in these exciting objects. We shall use a new stellar atmosphere code that includes the effects of sphericity, expansion, and numerous lines to calculate model atmospheres for novae at maximum. This same code is being used on comparable studies of SN 1987A.

This will allow us to determine the abundances for novae in a completely independent way from the commonly used nebular studies of the emission lines seen much later in the outburst when the density has dropped to where photoionization and recombination are the only important factors effecting the line strengths.

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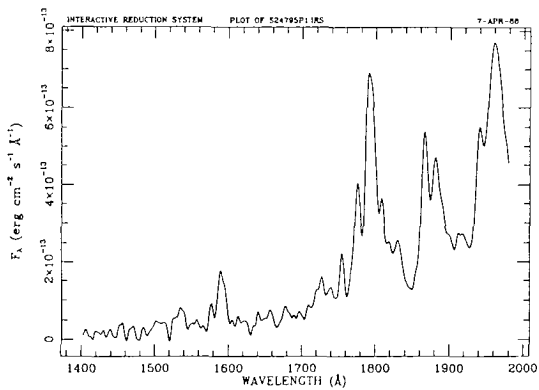
Figure 3a. The SWP image of Nova Vul 1984 #2 obtained on January 1, 1985 just a few days after discovery. Most of the same lines are present as in Nova Vul 1984 #1 but the relative strengths differ. This may be caused by either a real abundance difference or because of differences in the atmospheric conditions.
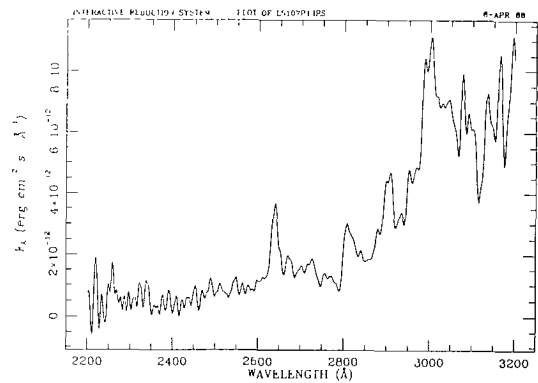
Figure 3b. The LWP image of Nova Vul 1984 #2 obtained at the same time as the SWP image in Figure 3a. Note the strong P Cygni profile of Mg II 2800Å. Note the difference in scaling from Figure 3a to 3b.
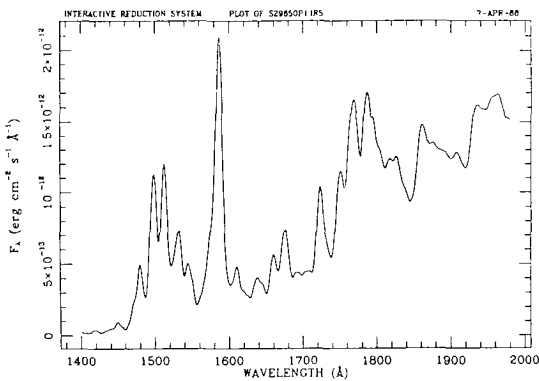

Figure 4a. The SWP image of Nova Andromeda 1986 obtained in December 1986 about 5 days after discovery. Again, note the striking similarity in the lines present in all three SWP spectra.
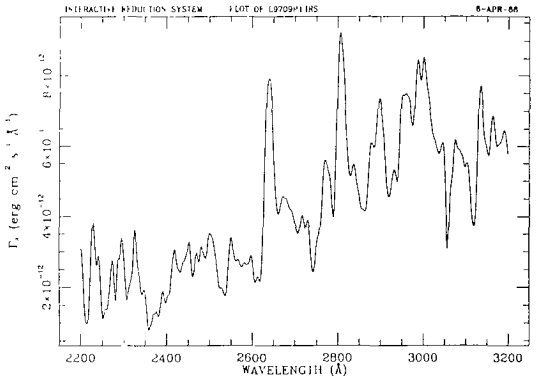
Figure 4b. The LWP image of Nova Andromeda 1986 obtained just after the SWP image. In this spectrum it appears that Mg II 2800Å is completely in absorption. In fact, Mg II was never very strong in this nova. Note the difference in scaling from Figure 4a to 4b.